Preliminary study on acoustic annoyance perception in virtual reality

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Introduction

Haptic research presents its own challenges due to its multidisciplinary scope, ranging from perceptual research to the development of actuation and sensing technologies, and their implementation on end-products [1]. Haptic gloves are a recurrent end-goal in this field, however their design is limited by the conflict that arises between high demanding requirements, the high sensitivity of human hands, and the existing devices. Sensing technologies have progressed, being currently feasible to implement compact sensors for human motion detection, although it's a field that keeps evolving and researching other aspects such as tactile sensing [2]. Actuation, on the other hand, hasn't reached that level of compactness, and the choice of actuators in haptic glove design commonly deals with various requirements and technical specifications, trying to reach a trade-off between them, e.g. more actuation capabilities require a higher volume and weight.

As mentioned in [3], there are multiple factors to consider, however in haptic design, acoustics is rarely taken into consideration. But actuators, and more specifically force feedback actuators, commonly produce acoustic noise when operating. In Virtual Reality (VR) applications, where users may have visual, audible and tactile cues, it may affect the immersion and, therefore, the overall experience. This aspect has been researched in previous works. A first analysis is made in [4], where different actuation technologies (geared DC motors, stepper motors and servomotors), suitable for force and kinaesthetic feedback, were recorded during operation and their sounds presented to various subjects for perceived noise evaluation. Stepper motors and servomotors presented the best perceived annoyance results. In a following work [5], servomotors' perception was further researched. In this case, six different models were measured in three different load conditions (50, 100 and 200 grams) while performing a similar motion. The actuators used in both experiments are shown in Fig. 1.

However, in such studies motor sounds were analyzed with test participants performing a passive role, meaning that they exclusively listened to the sounds, with no other acoustic, visual or tactile cues being applied. Thus, their attention was solely focused on the noises and the acoustic sense. However, a VR application is a multisensory experience, where acoustic, visual and sometimes haptic stimuli are used. Depending on the situation, users may also have an active role, where they must interact actively with their environment, being not only observers but also actors. In this work, a different experimental setup is organized to delve into such questions.

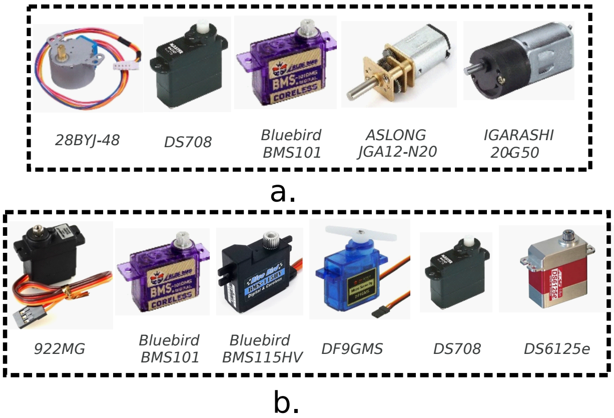

Figure 1: Motors used for analysis of perceived annoyance a) Different actuator technologies [4]. b) Servomotor comparison [5].

Experimental setup

As a continuation of such previous work in [5], here an experimental test bench with VR for sound evaluation is designed and presented. It aims to include visual, acoustic and haptic stimuli. Additionally, in contrast with prior experiments, this setup requires to perform a task, in order to include an additional cognitive effort and attention from the user.

For such test bench different technologies are required. First of all, the Virtual Reality framework to be used is CHAI3D [6], an open source framework which allows haptic implementation in VR. With regard to haptics, a force feedback glove is used. This device is designed as an exoskeleton, being able to adapt to different hand and finger sizes, due to its linkage design. Its stimulation areas are the index finger and the thumb, including position sensors for detecting and quantifying overall finger motion, and a 9-DOF inertial measurement unit (IMU) for detection of the hand's motion and tilt. Regarding actuation capabilities, the chosen actuator is the BMS101, which in the prior experiments [4, 5] presented low perceived annoyance. Two are implemented, one per finger, alongside a brake mechanism, in order to generate a blocking force on the fingers when they close. This is a boundary type of feedback, meaning that they produce stiff kinaesthetic feedback, able to stop the motion of the fingers. With its design it may only block the closing motion of the fingers, but allows free motion of the hand in the opening direction. This device requires a USB serial connection with the computer station for communicating with the VR suite, and an external 5VDC-1A power supply for the actuation system.

Although this force feedback glove uses BMS101 actuators, and thus they are already a source of noise, it is of interest to have the possibility of playing any type of motor sounds, in order to analyze the perception of sound feedback. CHAI3D allows for the implementation of sound sources, and in this setup it's programmed to play the BMS101 motion sounds every time force feedback is activated or deactivated, using here DT990PRO 250 Ohms headphones by Beyerdynamic. As there are two actuators, two identical sound sources are implemented in the simulation. It's also worth mentioning that two different motor sounds are used, one when the motor applies feedback, and another when it releases the finger, thus allowing free motion, lasting each sound 400 ms. These sounds are extracted from the recording of a BMS101 used in [5], more specifically from the low weight scenario (50 grams).

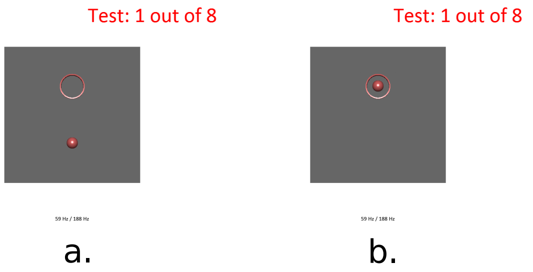

Figure 2: Example of the task to perform, showing the sphere to pick up, and the target ring where it should be placed. a) Initial position. b) Target position.

Both the force and acoustic feedback modalities are integrated in CHAI3D, where the VR environment that combines them alongside with visual cues is programmed. The task consists of controlling a sphere, by grabbing and placing it inside a target ring, where it is dropped, completing then the task, as shown in Fig. 2. There are various details to be mentioned in that regard. First the picking and dropping phase. At the beginning of the experiment the calibration of the finger motion range is carried out. Then, during the experiment, if the participant wants to pick the sphere, he or she should perform a pinching motion, meaning to close both the index finger and the thumb. When a finger reaches the 65% of total motion range, then the force feedback is activated and applied to it, while hearing the corresponding motor sound in the headphones. When both fingers are closed and with force feedback (therefore locked), then control of the sphere's position is activated. Its motion is, however, not based on the absolute position of the hand, meaning that displacement of the hand to the left doesn't translate into the displacement of the sphere to the left. Here position control is based on the angular position of the hand, as depicted on Fig. 3. As the virtual reality is 2D, only two types of input are needed, using for that goal the roll and pitch motions. As shown in the picture, if the hand rotates to the right (positive roll), the sphere will move to the right and viceversa. Similar for moving forward and backwards in relation with pitch's rotation. The resting position is ideally for the hand is therefore when it's like in the picture, parallel to the ground, with the palm downwards. However, every time the user picks the sphere at the beginning of each stimulus, such reference is reset, in order to make it adaptive to every test subject and stimulus.

For releasing the sphere into the ring the user has to open both fingers, finishing then the task and automatically proceeding to the next stimulus. If during the task the user opens one of the fingers, the sphere is released, so both fingers must be closed in order to move the sphere.

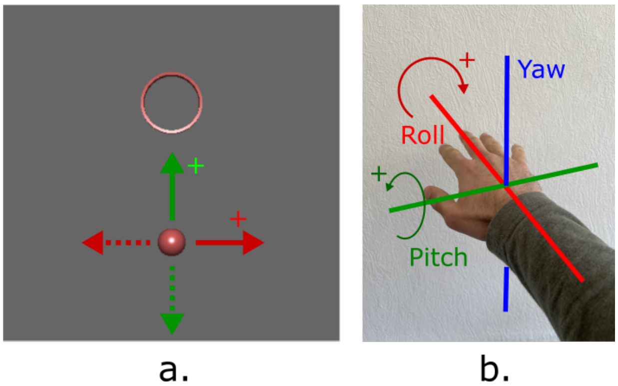

Figure 3: Reference system for hand motion and its effect on the control of the position of the sphere. a) Reference system in the VR suite. b) Reference system in the hand.

Experiment Preparation

For this experiment there are 8 stimuli in total, being the varying parameter the locations of the ring and the sphere, being always on opposing sides of the square area (in grey). Force and acoustic feedback remain constant. For every test subject the order of such locations is randomized. In total 20 test subjects, 16 males and 4 females, took part in the experiment, with ages ranging between 22 and 42 years, being 19 right handed and 1 left handed. No prior training was executed. Users were explained the experiment in detail beforehand, and the experiment supervisor was present during the entire experiment. After its completion, the participants answered a series of questions about the sounds, the haptic glove and the overall experiment (Fig. 4). A semantic test is applied, with users rating between 0 and 100 each question according to the scale displayed on the picture. Additionally, participants' personal insights were also asked for.

Results

Ratings for every question are displayed in Fig. 5. From a first analysis it's visible that the sounds were perceivable, presenting the first question an interquartile range (IQR) of 75-87.75, which corresponds to the "Very - Extremely" range in the semantic scale. However, on the other hand the annoyance ratings are relatively low, with IQR between 7.5 - 46.25, below medium ratings and with a me-

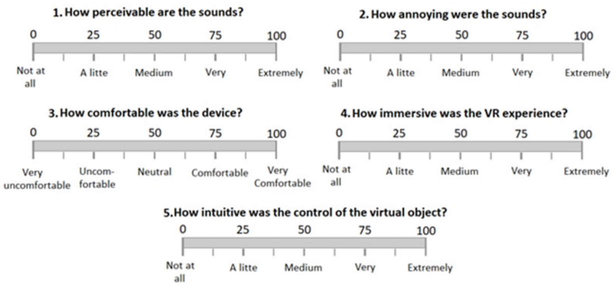

Figure 4: Post-experiment questionnaire.

dian value of 20. Besides acoustics, the other questions focus on the VR setup. The device's comfort presents mostly neutral ratings with a slightly positive rating of its comfortability, as the IQR is between 38.75-75. With regard to the immersion of the experiment, it's between mostly medium to high values (IQR of 47.5-77.5). The intuitiveness of the control of the sphere presents similar results (IQR 50-76.25).

Additionally, it is analysed whether there are correlations between the questions, applying for that a test for Pearson's correlation test, obtaining the p-values for testing non-correlation. Such values are shown in Table 1. An interesting possible correlation is found between the three VR related questions, that is, device comfort, immersion, and intuitive control (Q3, Q4 and Q5). With regard to comfort, it presents p-values of 0.05 (Q3-Q4) and 0.041 (Q3-Q5), which may indicate statistical significance, and therefore a possible correlation with immersion and how intuitive was the control. Immersion and control present a p-value of 0.00028, therefore, it's highly statistically significant and a high correlation between them is strongly suggested. Another interesting possible correlation is found between sound's perception (Q1) and control (Q5), with a p-value of 0.028. With regard to the other questions, no further significant correlations were detected.

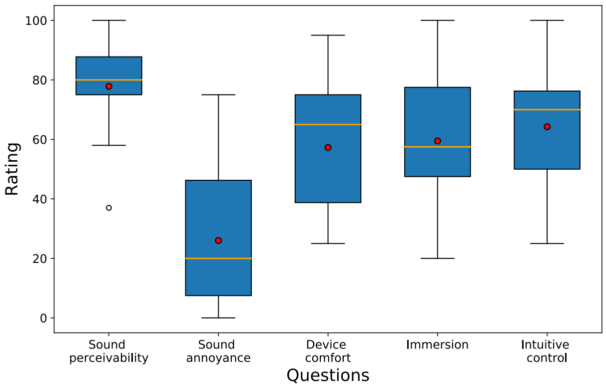

Figure 5: Questionnaire ratings, with the mean values represented as red dots, and the median values as orange lines.

As the focus of this work is laid on the perceived acoustic annoyance, a comparison with the results from prior work in [5] is done. Such previous results will be referred as the passive case, and current work's results will be referred as the active case, in relation with the role of the users in the experiment. Therefore, a independent groups t-test is to be applied. But first both data sets are checked for the necessary assumptions of the t-test, which are homogeneity of variance, and an approximately normal distribution. For normality, the Shapiro-Wilk test is applied to each data set, obtaining a p-value of 0.28 for the passive data, and 0.05 for the active one. Although for the passive case it may be said that data is probably normally distributed, for the active case the p-value is in the threshold of statistical significance. Due to that, for testing whether the variance is similar for both data sets, two tests are performed: Bartlett's test, which requires normal distributions, and Levene's test, which is more robust for non-normal distributions. Both have the null hypothesis that input samples are from populations with equal variances. The resulting p-values are 0.96 with Bartlett's and 0.89 with Levene's, therefore it's strongly suggested that variances may be equal for both populations. The t-test is therefore applied, with the null hypothesis that that 2 both data sets have identical average (expected) values, and it is performed with two alternative hypothesis: first that the means of the distributions underlying the samples are unequal, and second, that the mean of the distribution underlying the passive case is greater than the mean of the active case. For the first alternative hypothesis the p-value was 0.08, therefore not statistically significant. However, for the second case it's 0.043, being thus possible that there is in fact a difference between the data sets.

Table 1: Pearson correlation test - P-values for non-correlation between each question's results. (Q1:Perceiving sound, Q2:Sound annoyance, Q3:Device comfort, Q4:Immersion, Q5:Intuitive control)

P-Value	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**
Q1	0	0.46	0.43	0.38	0.028
Q2	0.46	0	0.24	0.11	0.25
Q3	0.43	0.24	0	0.05	0.041
Q4	0.38	0.11	0.05	0	0.00028
Q5	0.028	0.25	0.041	0.00028	0

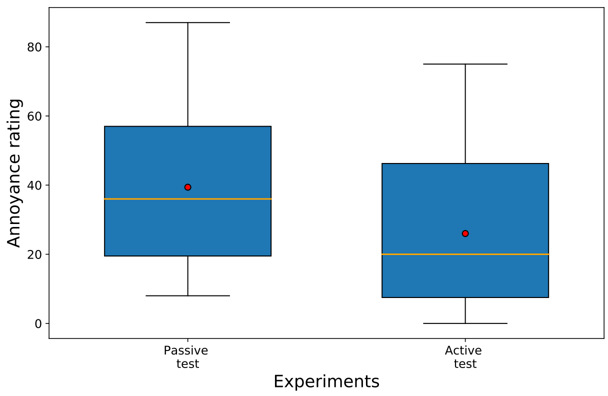

Figure 6: Comparison of perceived annoyance results between the passive and active scenarios.

Discussion

In this work a multi-sensory virtual reality setup is presented and applied for perceived annoyance evaluation of motor sounds. Preliminary results suggest that sounds presented high perceivability, although their annoyance ratings were relatively low. A first comparison with previous experiments suggests that perceived annoyance for the same sounds decreases when there is a task to perform and there are multiple senses involved (visual, acoustic and haptic). With regard to comfort, immersion and control, ratings were neutral and/or slightly positive. However, multiple aspects, both in the setup and in the experiment, are suitable for further improvement. With regard to the hardware, the force feedback glove should be modified in order to have a better and more comfortable attachment, as for some hand sizes the device didn't adapt so well. Additionally, force feedback didn't operate perfectly in every occasion, due to a combined effect of the force transmission mechanism and the VR's control loop. With regard to motion control, several subjects mentioned that it was perceived as counter-intuitive, both with regard to the type of rotation direction for the hand, and the type of motion, as here an angular position is used to create spatial displacement. An alternative would be to implement additional sensors for detecting the relative or absolute position of the hand, in order to apply a more natural type of control, although it would increase the complexity of the system. Another alternative would be to analyse whether another type of rotational motion would be more intuitive for the users.

With regard to acoustic feedback, multiple aspects are susceptible to improvement. First, with the current system there is a delay in the sound, which was detected by various subjects. This delay is produced by a combined effect of the sound's duration (400 ms) and the programming. Therefore, a better synchronization of the various types of stimuli would be necessary. Besides the synchronization, another proposal would be to perform a comparison with an improved version of this setup between different actuator sounds, such as in the previous studies, and/or comparing it also with a scenario where no motor sound is applied. In addition, sounds may also be included not only as a source of annoyance, but as actual sound feedback that may enhance and complement the visual and haptic domains, e.g. indicating how well the task is being performed/completed. Another possible modification, that may affect the visual and acoustic senses, would be to use a VR headset instead of a monitor, as the level of immersion may be higher. One possible hypothesis would be that the use of a VR headset could provide enough acoustic isolation, so motor sounds from the actual glove may not be heard. One last proposal would be to implement a data recording system within the VR application, in order to measure the user's performance, in aspects such as task completion time or task accuracy. These type of metrics may provide insightful information when comparing different types of sound feedback, force feedback stimuli and devices, or types of tasks, among other possible factors.

Acknowledgment

Funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universität Dresden.

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